TECHNICAL NOTE R-192

A FEASIBILITY STUDY OF AN ADVANCED SPACE ENVIRONMENTAL EFFECTS SENSOR

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ABSTRACT

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This report summarizes the results of a feasibility study of an Advanced Space Environmental Effects Sensor (ASEES) using active control of sensor temperature. A detailed thermal analysis is presented followed by conceptual designs of three possible systems, two using active heating and a third using a thermoelectric module for active cooling/heating. Guidelines for a stability and error analysis are included as well as recommendations for further studies.

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INTRODUCTION

The need exists for a compact thermal sensor to be used in satellite experimentation for the measurement of solar, Earth IR, and albedo fluxes, and to evaluate thermal control coating stability. The Space Environmental Effects Sensor (SEES)[1] has been developed and flight tested (Pegasus satellite) to accomplish these objectives. The SEES consists of an aluminum disc, resistance thermometer, and case. The coated surface of the disc is exposed to 2π steradians of space and mounted in the case which is attached to the satellite. A resistance thermometer is attached to the side of the disc not exposed to space. This design requires thermal isolation between the disc and case to obtain accurate measurements. The thermal isolation necessary to achieve the desired accuracy was not obtained by the SEES primarily due to exchange of heat between the disc and case by radiation and conduction through the supporting structure.

A new concept, used in the Advanced Space Environmental Effects Sensor (ASEES), makes the disc temperature a controlled parameter and eliminates the problems of the SEES. In addition, the new system allows a more direct measurement of heat flow and permits a wider range of α/ε values.

A feasibility study has been made of the ASEES using active control of temperature. The basic technique involves maintaining the disc and case temperatures equal and constant. Two designs, active heating and active cooling/heating, were studied with consideration given to

- Thermal properties and behavior of disc and case in a space environment
- Component selection
- Active heating or cooling technique

- System design
- System error
- Reliability.

This report presents the conceptual designs of systems considered to be feasible. Previous interim reports[2, 3] have presented details of the analysis and design.

THERMAL ANALYSIS

In order to evaluate the electrical requirements for maintaining a sensor at a uniform temperature, it was necessary to determine the radiant energy exchange for the sensor. Since the objective of this study was a feasibility determination, one of the extreme cases was examined. This was the case where the sensor surface is normal to the incident solar radiation.

EQUILIBRIUM TEMPERATURES

The calculation of the radiation shape factors is based on methods described in Reference 1. The basic equation for the energy balance on the disc, without power supplied, is given by

$$\dot{T}_1 H_1 = \sum_{i=1}^{6} \dot{Q}_i = A_{11}\,\alpha_1\,S + A_{21}\,\alpha_1\,BS + A_{31}\,\varepsilon_1\,ES - A_{41}\,\sigma\,\varepsilon_1\,T_1^{\,4} + C_1(T_2 - T_1) + R_1\left[\left(\frac{T_2}{100}\right)^4 - \left(\frac{T_1}{100}\right)^4\right] \tag{1}$$

where

A_{11} - projected area of disc toward the sun

A_{21} - area function for albedo flux to disc

A_{31} - area function for Earth's IR flux to disc

A_{41} - area of disc

B - albedo constant

C_1 - total conductance from the disc to the case

E - Earth IR constant

H_1 - heat capacity of the uncoated disc

R_1 - radiance from the disc to the case

S - solar constant

T_1 - temperature of sensor

T_2 - temperature of case

α_1 - solar absorptance

ε_1 - IR emittance (or absorptance) of disc

σ - Stefan-Boltzmann constant

$\cdot$ - differential with respect to time.

Now the absorbed energy from space, $\dot{Q}_S$, is given by

$$\dot{Q}_S = A_{11}\,\alpha_1\,S + A_{21}\,\alpha_1\,BS + A_{31}\,\varepsilon_1\,ES \quad . \tag{2}$$

Rearranging

$$\frac{\dot{Q}_S}{\varepsilon_1 S} = \frac{\alpha_1}{\varepsilon_1}\,(A_{11} + BA_{21}) + EA_{31} \quad . \tag{3}$$

In the general case, the part of the earth and albedo flux which is viewed by the sensor falls into three classes: (a) the total area viewed is lighted by the sun, (b) the total area viewed is dark, (c) part of the area viewed is lighted by the sun and the remainder is dark. For low orbits only a small fraction of the orbital time is spent in the partially lighted region, therefore it was assumed that $A_{21} = A_{31}$ when the sensor was in the lighted region and $A_{21} = 0$ when the sensor was in the dark region. The partially lighted region was neglected. It was also assumed that the albedo and the earth's IR radiation emanate from the same point. The special case assumed above can be extended to a more general case by placing two or more sensors in orbit, one with a stable coating. The α/ε can then be evaluated with respect to the stable α. Also A_{21} can possibly be calculated from measurements taken with the sensor having the stable coating.

$$\frac{\dot{Q}_S}{\varepsilon_1 S} = \frac{\alpha_1}{\varepsilon_1} A_{11} + \left(\frac{\alpha_1}{\varepsilon_1} B + E\right) A_{31} \tag{4}$$

or

$$A_{31} = \frac{\dot{Q}_S - \alpha_1 A_{11} S}{\alpha_1 BS + \varepsilon_1 ES} \quad . \tag{5}$$

Also by substituting Equation 2 into Equation 1,

$$\dot{Q}_S = \dot{T}_1 H_1 - C_1(T_2 - T_1) - R_1\left[\left(\frac{T_2}{100}\right)^4 - \left(\frac{T_1}{100}\right)^4\right] + A_{41}\sigma\varepsilon_1 T_1 \ . \tag{6}$$

Now using the temperature time history as given in Reference 1, the constants derived for the disc, and the constants ($S = 1333$ w/m^2, $B = 0.40$, and $E = 0.168$), the area factor A_{31} is given by

$$A_{31} = \frac{\dot{Q}_S - 0.935}{681.4} \tag{7}$$

when the disc is not in the earth's shadow and by

$$A_{31} = \frac{\dot{Q}_S}{201.5} \tag{8}$$

when the disc is in the earth's shadow.

The values of A_{31} were determined as a function of position in orbit by using the slope of the temperature-time curves (Reference 1) and Equations 6, 7, and 8.

The equilibrium temperature, T_e, is the temperature the sensor will attain when it is in thermal equilibrium with the absorbed energy. Then

$$\dot{Q}_S = A_{41}\sigma\varepsilon_1 T_e^4 \tag{9}$$

or

$$A_{41} \sigma \varepsilon_1 T_e^4 = A_{11} \alpha_1 S + A_{21} \alpha_1 BS + A_{31} \varepsilon_1 ES \quad . \tag{10}$$

Now when the disc is perpendicular to the incident solar radiation, $A_{41} = A_{11}$, and using as before $A_{31} = A_{21}$, then

$$T_e^4 = \frac{\alpha_1}{\varepsilon_1} \frac{S}{\sigma} + \frac{A_{31}}{A_{41}} \frac{\alpha_1}{\varepsilon_1} B \frac{S}{\sigma} + \frac{A_{31}}{A_{41}} \frac{ES}{\sigma} \tag{11}$$

when the previously determined constants are used;

$$\left(\frac{T_e}{100}\right)^4 = \frac{\alpha_1}{\varepsilon_1} \left[235.1 \left(1 + 0.4 \frac{A_{31}}{A_{41}}\right)\right] + 39.5 \frac{A_{31}}{A_{41}} \tag{12}$$

when the sensor is in the sunlight; or

$$\left(\frac{T_e}{100}\right)^4 = 39.5 \frac{A_{31}}{A_{41}} \tag{13}$$

when the sensor is in the Earth's shadow. Calculated values of T_e are shown in Figure 1.

POWER REQUIREMENTS

The power input, P, for an isothermal disc ($T = T_s$) when its case is at the same temperature as the disc is given by

$$P = A_{41} \sigma \varepsilon_1 T_s^4 - A_{11} \alpha_1 S - A_{21} \alpha_1 BS - A_{31} \varepsilon_1 ES \quad . \tag{14}$$

Now referring to Equation 10, Equation 14 becomes

$$P = A_{41} \sigma \varepsilon_1 (T_s^4 - T_e^4) \tag{15}$$

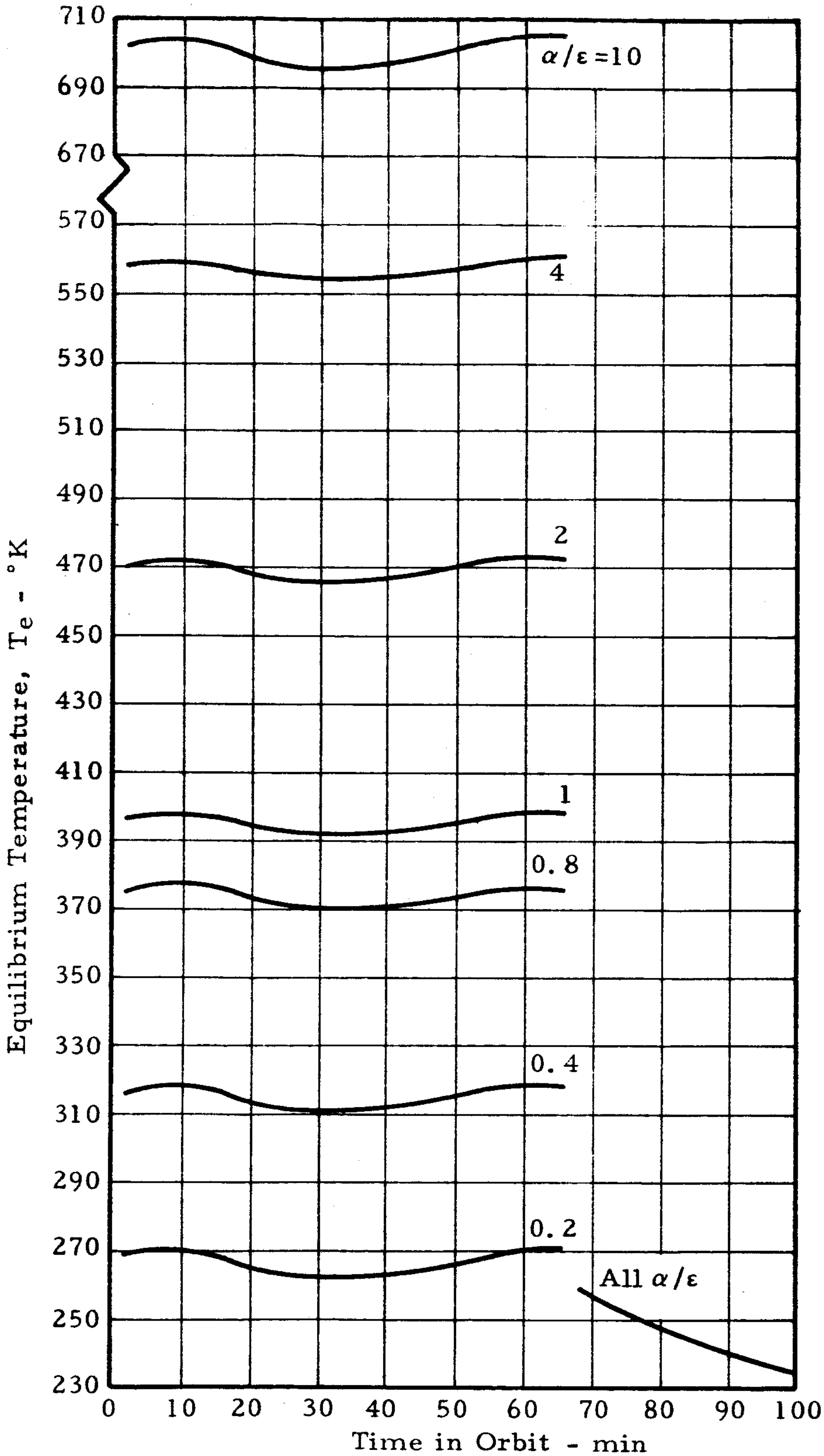

Figure 1. Equilibrium Temperature Versus Time for 100-Minute Orbit, MAS=0°

or for this case

$$P = 0.00442\, \varepsilon_1 \left[\left(\frac{T_s}{100} \right)^4 - \left(\frac{T_e}{100} \right)^4 \right] \quad .$$

Shown in Figure 2 are representative values for power requirements in the heating mode for several α/ε ratios. The values are based on the following parameters:

α/ε	α	ε	T_s
0.4	0.4	1.0	330
1.0	1.0	1.0	405
4.0	1.0	0.25	565

The sensor temperature, T_s, was chosen to be approximately five degrees Kelvin above the equilibrium temperature.

Figures 3 through 5 present representative values for power requirements for maintaining an isothermal disc with a cooling/heating mode of operation. Values are shown for several operating temperatures between the maximum and minimum equilibrium temperature.

The power values shown in these figures are the energy added or removed from the disc. The total power requirements must include energy for operating other elements of the system. Included in the Conclusions and Recommendations are estimates for total system power requirements.

DISC TEMPERATURE GRADIENT

One additional factor was examined during the thermal analysis. This was to estimate the temperature gradient across the disc. For either mode of operation a small area in the center of the disc must be used for a temperature sensor.

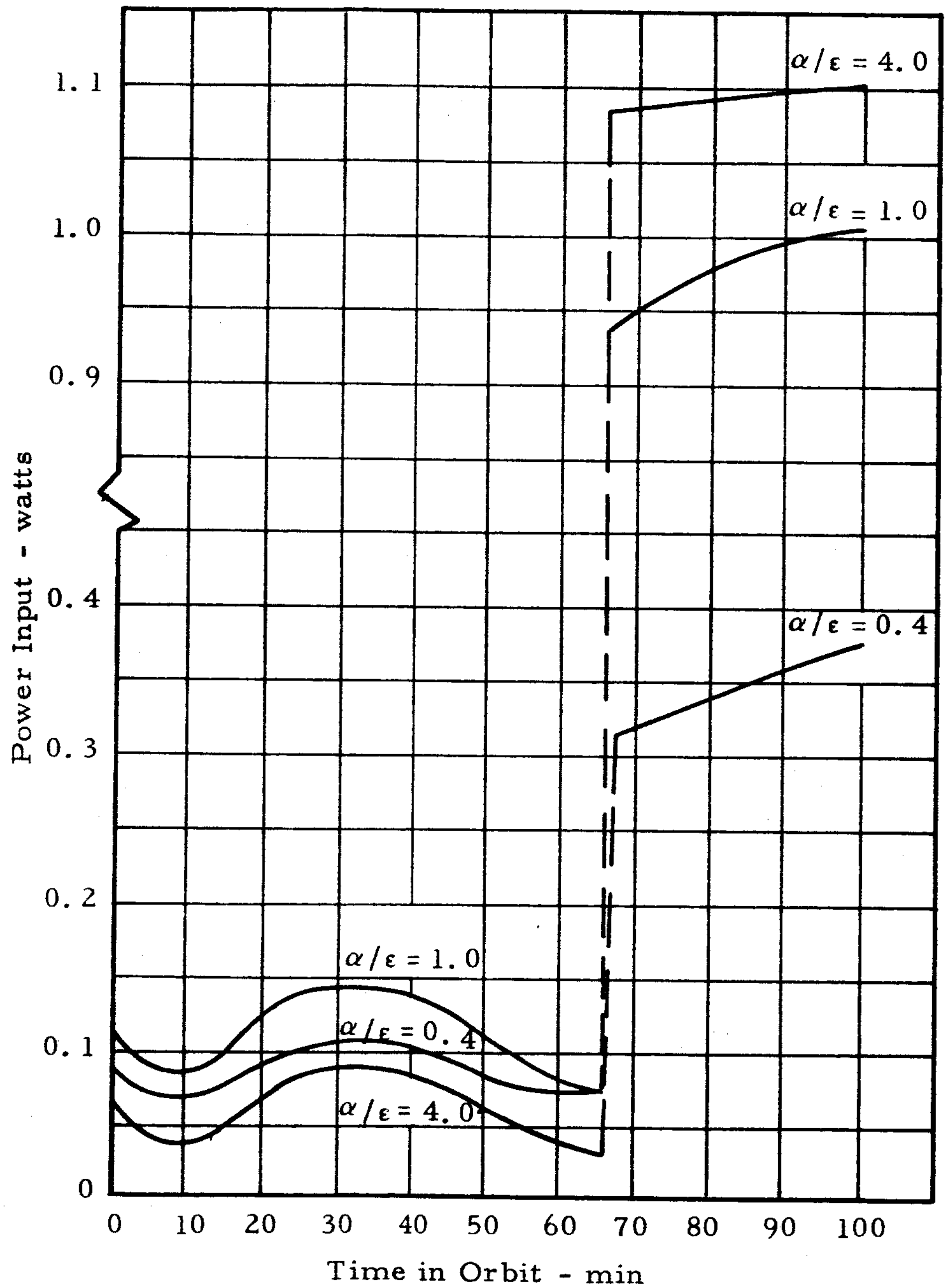

Figure 2. Power Versus Time Requirements for Heating Mode

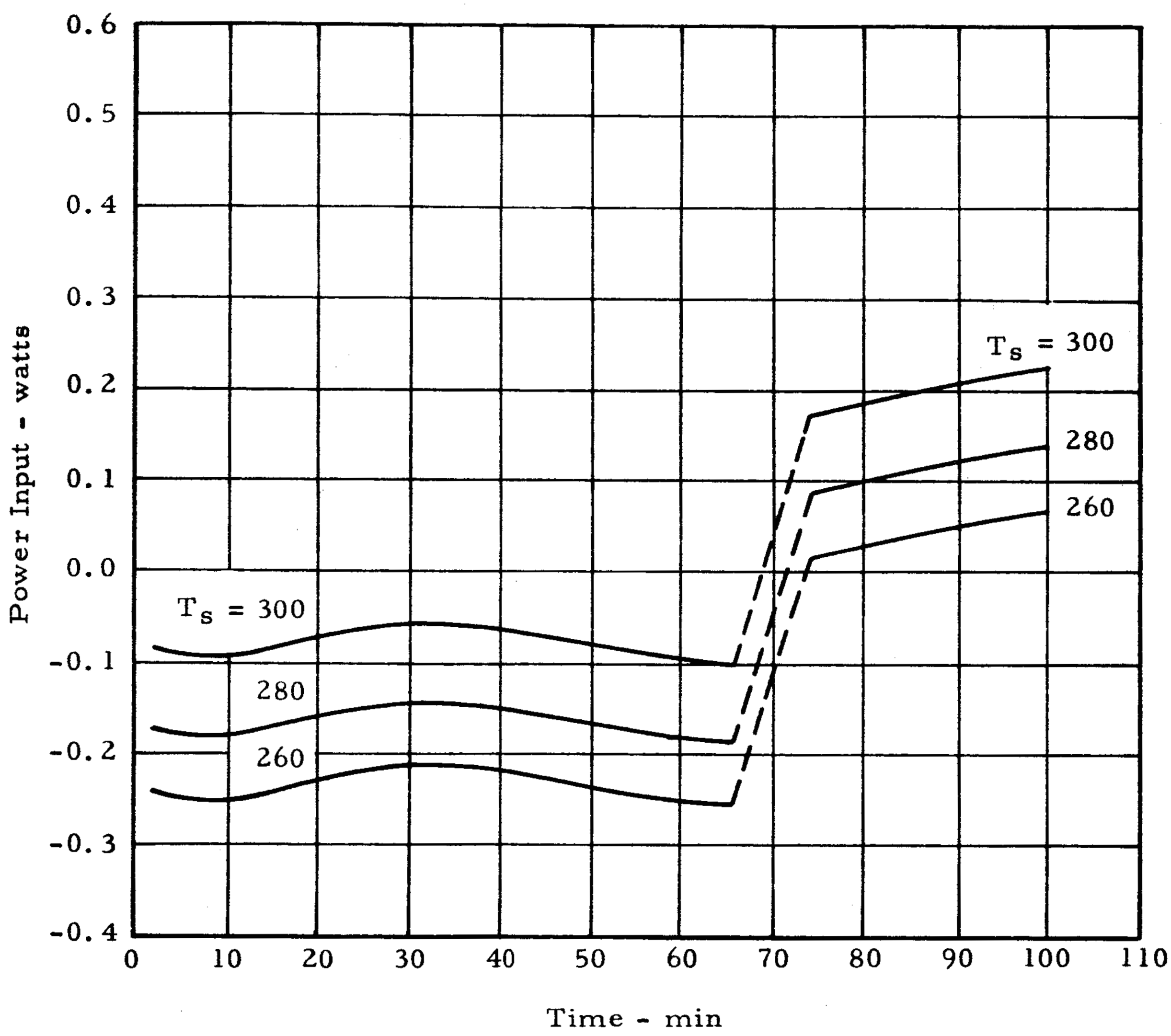

Figure 3. Power Versus Time Requirements for Heating - Cooling Mode (α/ε = 0.4; ε = 1.0)

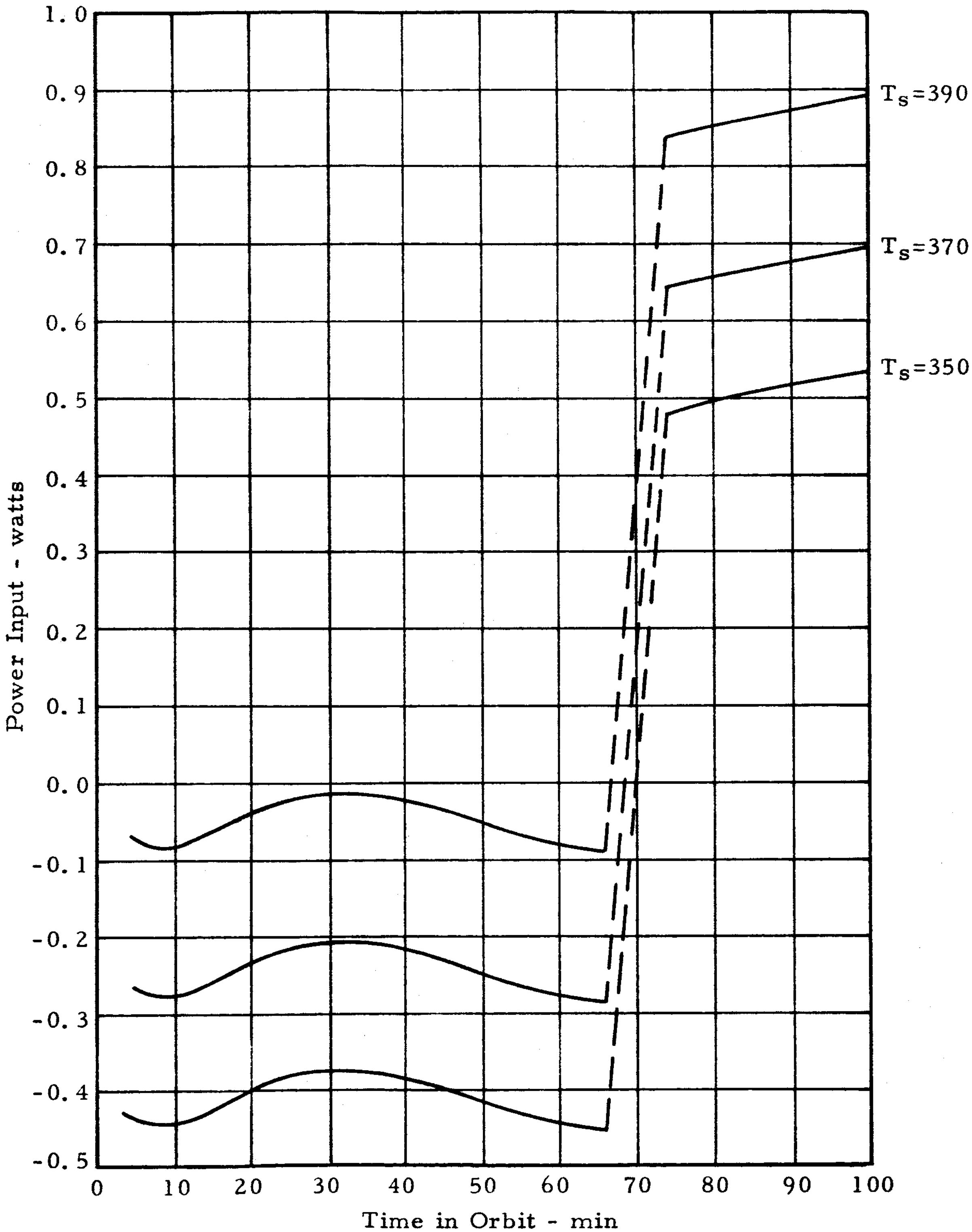

Figure 4. Power Versus Time Requirements for Heating-Cooling Mode ($\alpha/\varepsilon = 1.0$; $\varepsilon = 1.0$)

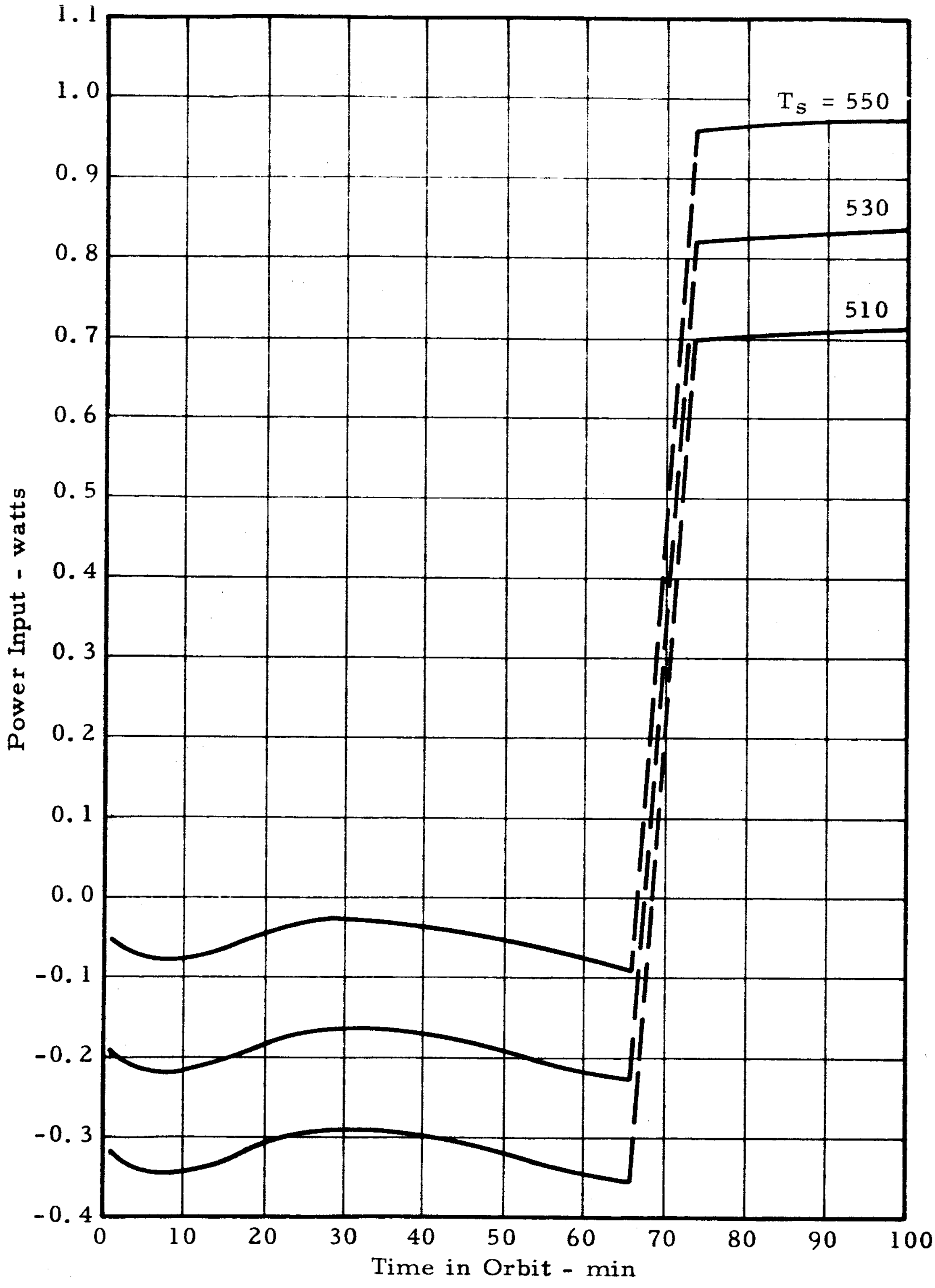

Figure 5. Power Versus Time Requirements for Heating-Cooling Mode (α/ε = 4; ε = 0.25)

The maximum temperature differential was estimated by assuming all of the energy required to heat or cool an area one cm in diameter located at the center of the disc would be transferred to or from the center and the outer edge of the disc. This leads to a temperature differential of approximately 0.2°K.

SYSTEM CONCEPTUAL DESIGNS

Conceptual designs for three systems are presented. Two of the systems are based on active heating with the sensor separate from the heater in one case and a combined heater-sensor in the other. The third system uses an active cooling/heating approach.

The proposed conceptual designs for the active heating systems will maintain the temperature of the disc at a constant level and equal to the case temperature. The zero temperature difference prevents any exchange of energy between the two through conduction or radiation. The constant level at which the disc and case temperatures are held is chosen slightly above the maximum equilibrium temperature. The equilibrium temperature is dependent on the α/ε ratio being tested. The incident energy on the disc is then measured indirectly by monitoring the power required to maintain this temperature.

The active cooling/heating approach utilizes a thermoelectric device which can both heat and cool the disc. The operating temperature is chosen to lie somewhere between the maximum and minimum equilibrium temperatures. As in the heating systems, the energy incident on the disc is measured by monitoring the current supplied to the thermoelectric device.

SEPARATE HEATER-SENSOR APPROACH

The conceptual design for the separate heater-sensor approach is shown in Figure 6. In this system, a platinum resistance thermometer is used to sense the temperature of the disc (or case) and a simple wire heater is used to supply the energy required to maintain the disc at a preselected temperature. As the system receives DC power from the satellite power system, it

- Converts the DC to AC and supplies the Comparator (modified Wheatstone bridge) with its driving voltage and the servo amplifier with its reference voltage, both being of the same frequency and in phase, and

- Converts the DC to a different level, supplies the AC amplifier with its collector supply, and the current controller with its source of prime power.

When the temperature of the disc (or case) is equal to the preselected operating temperature, the bridge is balanced and no voltage is present at the output terminals of the bridge. When the temperature of the disc is below or above the operating temperature, the bridge becomes unbalanced thus producing an AC error signal at the output. The amplitude of this error signal is proportional to the difference between the operating temperature and the actual temperature of the disc (or case). This signal is then passed through a constant gain AC amplifier which has a phase shift of $n \times 360°$ for $n = 1, 2, 3, \ldots$ The input to the AC-DC phase sensitive servo amplifier is in phase with the output signal from the bridge. The servo amplifier compares the phase of the input signal with the reference signal which is in phase with the driving voltage of the bridge. The AC input signal is converted to DC, the polarity of which depends on the phase between the reference and error signals. If the two signals as shown in Figure 7 are in phase, indicating that the temperature of the disc is below the desired value, a positive error signal is forwarded to the controller to supply power for the heater. If the two signals shown in Figure 8 are 180° out of phase, indicating that the temperature of the disc is above the desired value, the output polarity of the servo amplifier is reversed. This output is restricted from the controller input by a blocking diode preventing any control action. The output of the servo amplifier is filtered to remove the AC component of the error signal prior to being routed to the controller. The case control system operates exactly in the same manner. The system must be calibrated under "controlled" conditions to establish the relationship between the incoming energy and the heater current.

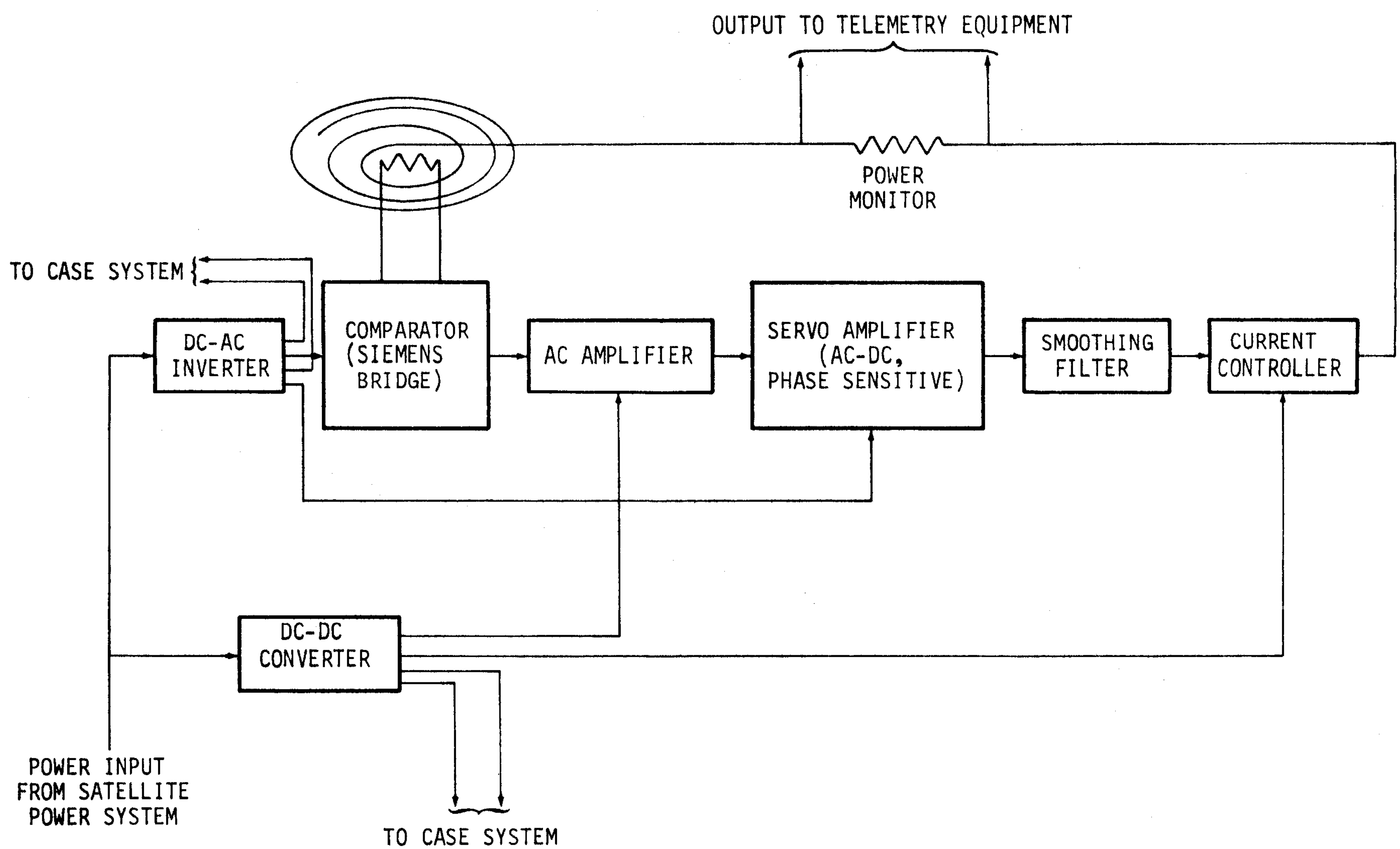

Figure 6. Heating System Employing Separate Heater and Sensor

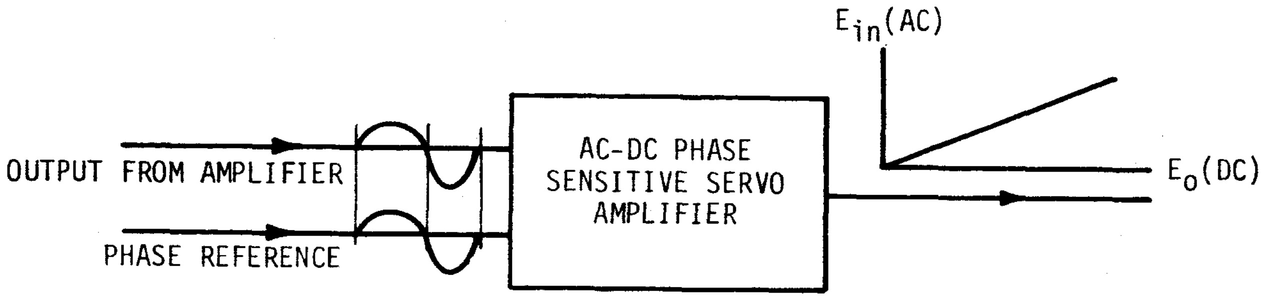

Figure 7. Output of Servo Amplifier when Input Signals are In Phase

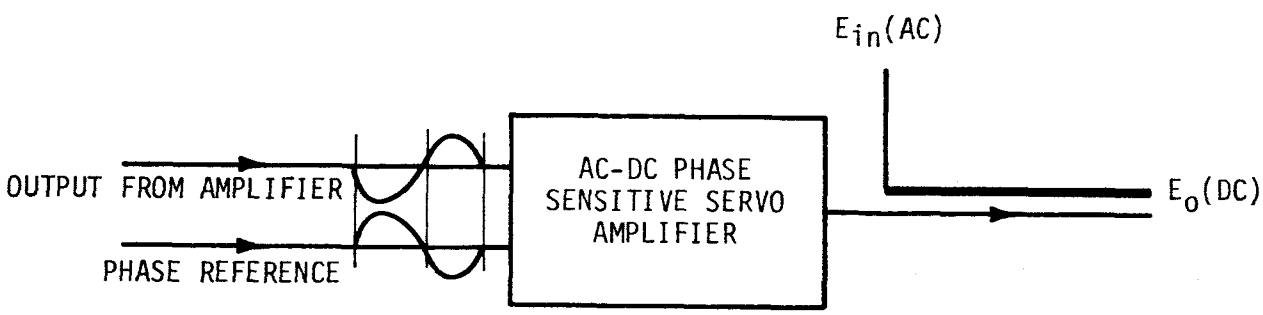

Figure 8. Output of Servo Amplifier when Inputs are 180° Out of Phase

The placement of the heater and the temperature sensor on the disc is an important consideration since the temperature gradient across the disc must be held lower than the system error by an order of magnitude to insure that the temperature sensed by the resistance thermometer is a true indication of the disc temperature. Two heater mounting configurations are shown in Figures 9 and 10. The heater shown in Figure 9 is arranged in concentric circles and electrically connected in series. This configuration will supply the power more evenly over the disc surface than the spiral arrangement shown in Figure 10. The concentric circle heater is slightly more expensive. Laboratory tests should be made to determine if the gradients of the spiral configuration are acceptable. For both heater configurations, the sensor is located in the center of the disc.

Similar conditions apply for the case heater configuration and sensor location. However, the sensor location is more critical since a larger area is to be heated and hence the temperature gradients will be greater. The case heater configuration shown in the cross-section view of Figure 11 is spirally wound down the inside of the case. The temperature sensor is centrally located on the bottom of the case. This location was chosen since a large portion of the error in the present system is attributed to conduction through the disc support members which are attached to the bottom of the case. The bottom of the case must be closely controlled to eliminate this contribution. The sides of the case in close proximity to the disc must also be closely controlled; hence a compromise in sensor location and in the number of turns of heater wire may have to be reached by experimental means. A top view of the case depicted in Figure 11 is shown in Figure 12.

COMBINED HEATER-SENSOR APPROACH

The previous heating system utilized the Comparator only to derive its error signal and a separate element to heat the disc or case. The approach represented by Figure 13 derives its error by this means

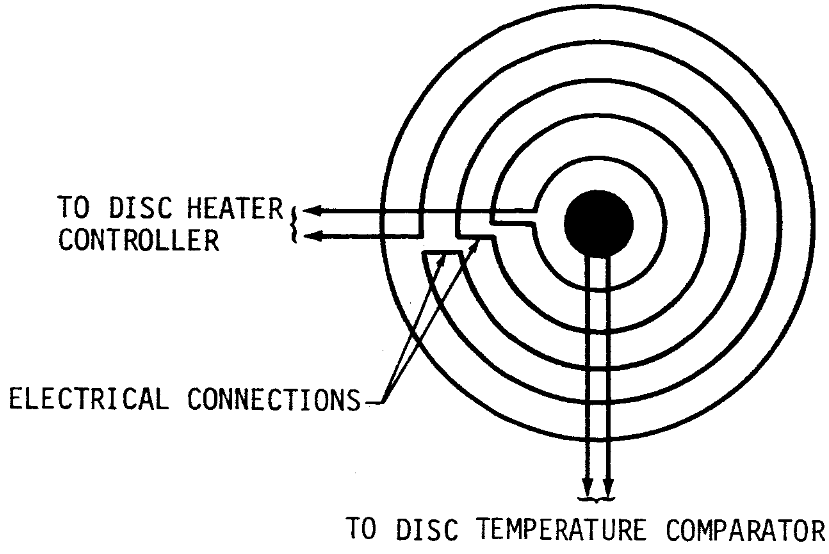

Figure 9. Bottom View of Disc Showing Sensor and Circular Heater

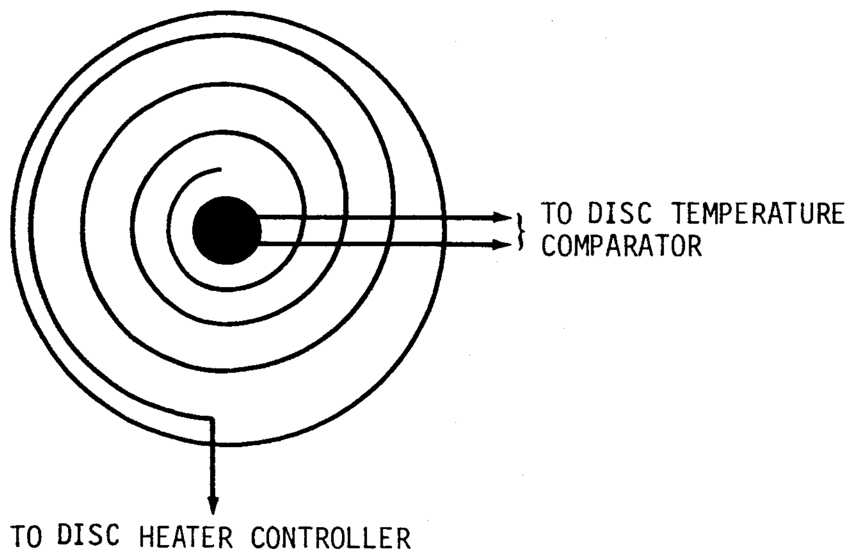

Figure 10. Bottom View of Disc Showing Sensor and Spiral Heater

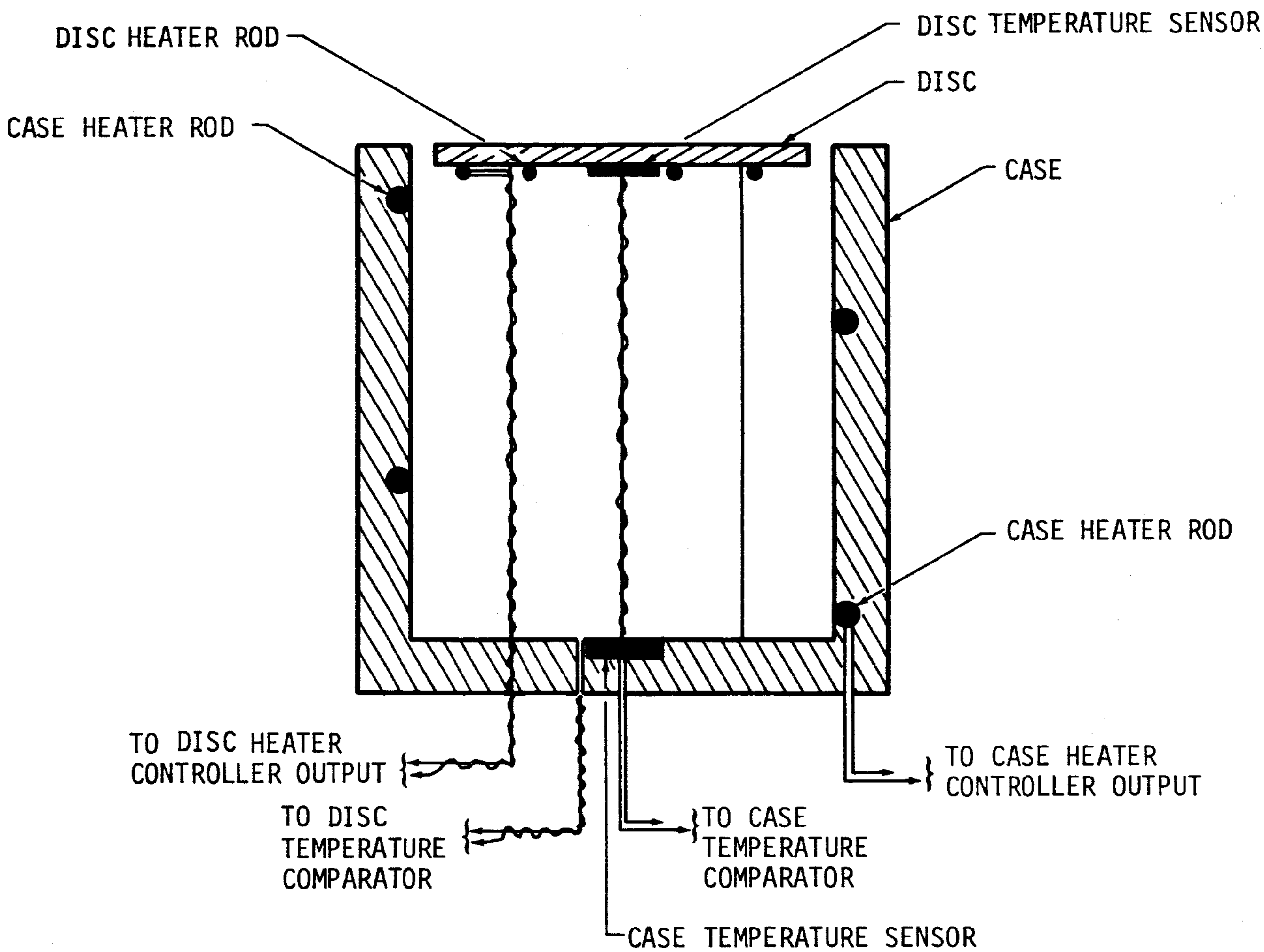

Figure 11. Cross Sectional View of Case and Disc Showing Possible Heater and Sensor Locations

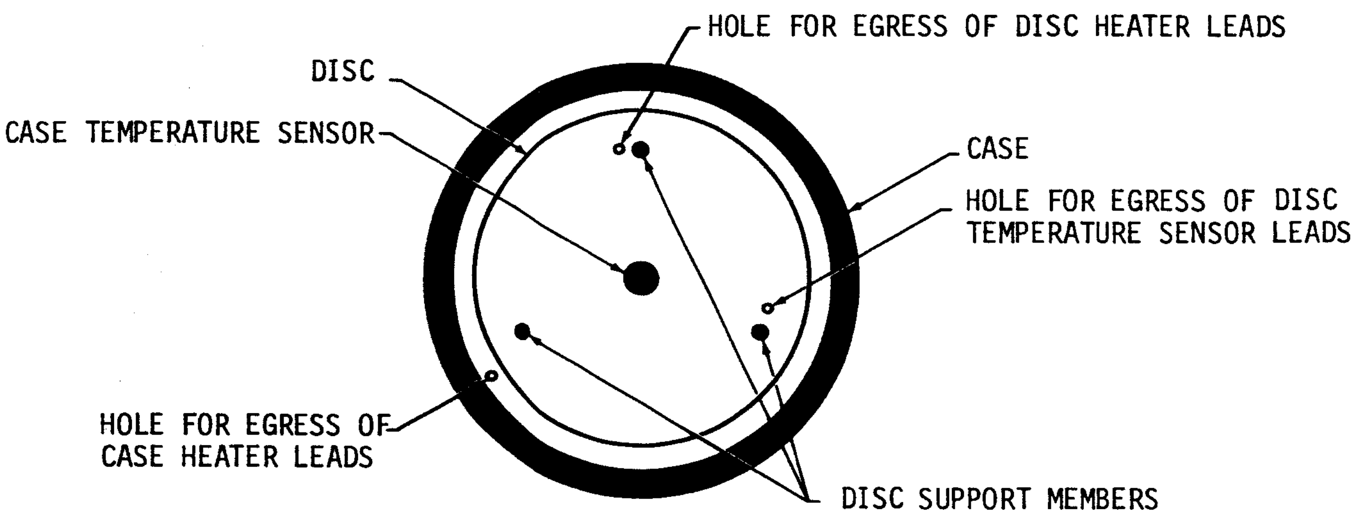

Figure 12. Top View of Case Showing Sensor Location

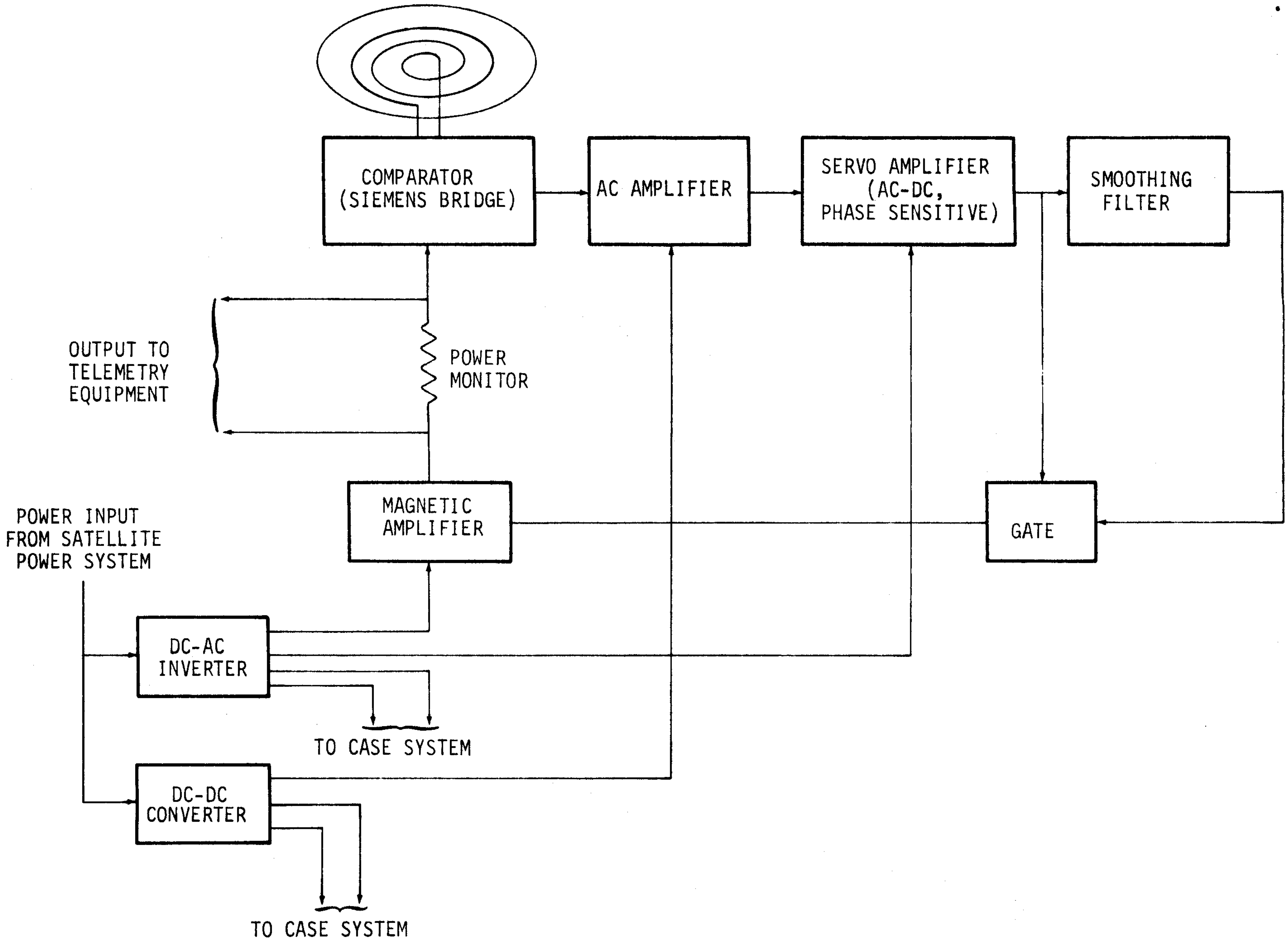

Figure 13. Heating System Employing a Single Element as Both Heater and Sensor

and supplies the heating power through the Comparator. That is, the driving function of the bridge has the current capacity that it may deliver sufficient power to the heater which is also the temperature sensing element. Consider the diagram of Figure 13 and assume some error signal is present at the output of the Comparator. This signal is first passed through a constant gain AC amplifier which has a phase shift of $n \times 360°$ for $n = 1, 2, 3, \ldots$ This output is sent to the AC-DC phase sensitive servo amplifier whose operation is described in the previous system. However, at the output of the servo amplifier, the signal goes to the smoothing filter and also to a transistor gate which either allows the DC signal, which is proportional to the error, to control the magnetic amplifier when positive or simply leaves this line open when negative which puts no voltage on the control winding. The state of this gate is dependent on the magnitude and phase of the error signal. Assuming that the error signal is large enough to open the gate, the DC error signal is then applied to the control windings of the magnetic amplifier allowing more current to flow into the bridge and through the heater/sensor. This increase in current causes more power to be dissipated in the heater/sensor. An increase in the resistance of the unit results, thus forcing the bridge toward a balanced condition which reduces the amplitude of the error signal. This process continues until the output of bridge is so small that the gate is closed. The magnetic amplifier is turned off and the current flowing through the element is reduced to almost zero. If the current were actually reduced to zero, the system would be completely locked since no error signal could ever be derived with no input voltage. There is some output to the bridge even when the control current is zero since the magnetic amplifier requires some magnetizing current to establish the flux in the core. This magnetizing current provides the necessary signal for error detection. The presence of this small residual error requires the gate in the control winding circuit. If this gate were not present, the small residual voltage would be interpreted as an error signal and sent to the control winding of the magnetic amplifier to call for more current. The magnitude of the residual voltage appearing across the bridge can be controlled to some extent by placing a resistor in series with the magnetic amplifier and the bridge.

Since this system uses one element to both heat and sense, the response of the system will be faster than the separate heater-sensor system due to the time lag of the separate sensor. However, this system assumes that the temperature of the disc is exactly and instantaneously that of the heater/sensor, hence; it is likely that heater density must be greater and/or the geometrical configuration more critical. The configuration of Figures 9 and 10 can be applied to this system but that shown in Figure 9 will probably prove to be more satisfactory.

ACTIVE COOLING-HEATING APPROACH

An ASEES which employs two stacked thermoelectric modules is shown in Figure 14. The operation of this sensor is based on the following equation:[3,4]

$$Q = \alpha\, T_c\, I - \frac{1}{2}\, I^2 R - K\, \Delta T \tag{17}$$

where

- Q - heat transferred from the cold surface to heat sink (watts)
- α - Seebeck coefficient (volts/°K)
- T_c - cold junction temperature (°K)
- I - electrical current through the thermoelectric device (amps) (I is replaced by -I when in the heating mode)
- R - resistance of the thermoelectric device (ohms)
- K - thermoelectric conductivity of thermoelectric device (watts/°K)
- ΔT - the temperature differential between the heat sink and the cold surface ($\Delta T = T_{HS} - T_c$) (°K).

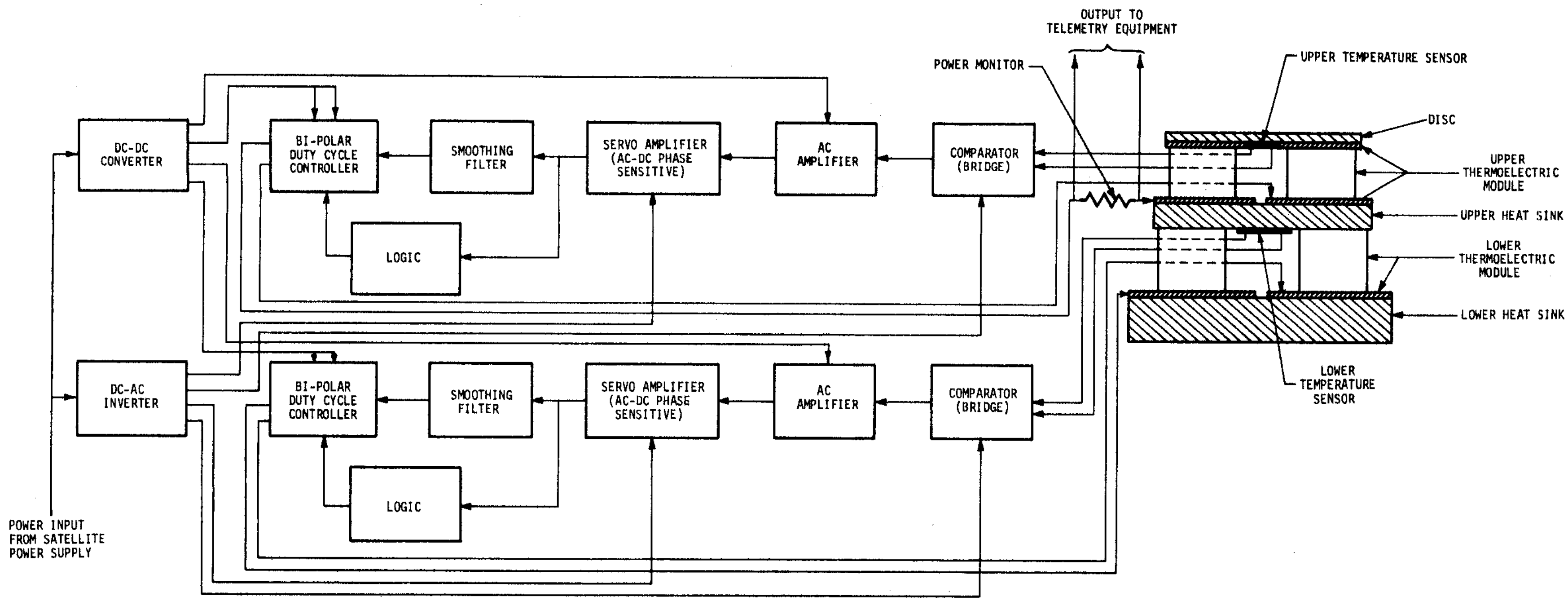

Figure 14. An Advanced Space Environmental Effects Sensor Utilizing a Thermoelectric Device

As shown in Figure 14, the disc is mounted on top of the upper thermoelectric module. The heat sink for the upper module is the cold surface of the lower module. The idea of the system is to maintain the disc at some preselected temperature (somewhere between the maximum and minimum values of equilibrium temperature for any α to ε ratio) either by adding or removing heat via the upper module. In order that this may be accomplished, the ΔT of the upper module must be kept constant so that the heat added or removed is directly proportional to the current input. Hence, the function of the lower module is simply to maintain the upper heat sink at a constant temperature and equal to disc temperature. The systems which control the upper and lower modules are identical; the only exception being that the system of the upper module contains a power monitor which supplies the signal to the telemetry equipment. Since the two systems are identical, an explanation will only be given for the upper module system assuming that the upper heat sink is being held at its prescribed temperature.

Consider the case where the disc is subjected to an increase in incoming energy which tends to raise its temperature above the operating value. This increase in temperature will be sensed by comparator and present an error signal, which is in phase with the bridge driving function, to the AC amplifier. The output of the amplifier is then fed to the servo amplifier which compares the phase relationship of its input signal and its reference signal. Since the two signals are in phase, the output of the servo amplifier is a positive DC level proportional to the temperature error. This DC signal is filtered and then supplied to the duty cycle controller but at the same time is sent through a logic gate which selects the proper polarity of the output of the duty cycle controller. Since the temperature of the disc is attempting to go above the reference temperature, the selection in this case would be to supply a positive current. This current is then supplied to upper thermoelectric module which tends to lower the temperature of the disc, lower the error signal and finally reduce the disc temperature to the reference value. Now consider the case where the temperature of the disc attempts to go below the desired value. In this case the error signal would be 180° out of phase with the bridge driving function. This difference in phase would then be sensed by the servo amplifier thus reversing the polarity of the duty cycle controller output and supplying current in such a direction as to cause the disc to be heated by the upper module. Again, this continues until no error signal is sensed and the temperature is returned to its proper value. The lower thermoelectric module system operates in exactly the same manner but its disturbance is due to the exchange of energy between the disc and the upper module.

DESCRIPTIONS OF SYSTEM ELEMENTS

Although the basic approach of the heating and cooling/heating systems are entirely different, their control systems are essentially the same and consequently contain practically the same elements. Descriptions of the major elements of each system are given in this section and, if not otherwise noted, the same description applies for each system. Previous reports[2, 3] have presented trade-off analyses of many of these elements.

DC-DC Converter

A DC-DC converter is an electrical device which receives a DC voltage of a certain magnitude with a given regulation and converts this voltage to another DC level with possibly a different figure of regulation. In both the heating system and the cooling/heating system the purpose of the DC-DC converter is twofold: 1) to provide the necessary supply voltage for the AC amplifier, and 2) to supply the current controller with the power required by the heater or the thermoelectric device.

Since the AC amplifier in both systems is amplifying signals of approximately the same level, their supply voltages can be of equal value.

The choice of this value is dependent on the transistors used in the amplifier. Many transistors are available which can be used for this application that operate from a supply voltage of 12 volts, hence one output of the DC-DC converter can be specified as 12 volts typically. The regulation requirement of this output is dependent on the type of amplifier but since most satellite sources vary from 28 to 32 volts, some improvement in regulation may be necessary. The ripple factor of this line could affect the operation of the overall system but if this is kept within a reasonable value, no influence is anticipated.

A second output is required from the DC-DC converter for the heating system, the purpose of which is to supply the necessary supply voltage required by the heaters. Since the maximum voltage required occurs when the α to ε ratio is 10, an output with this value could be used for all values of α/ε. However, this approach would produce an undue power loss in the controller for low values of α/ε since the difference between the supply voltage and the voltage dropped across the heater must be dropped across the transistor of the controller. This loss can be minimized by providing an output voltage which is variable over the required voltage range. The output would be set with only one adjustment prior to launch after the α to ε ratio of the coating is known.

The calculated voltage requirements for the case heater vary from approximately 8 to 2 volts while those for the disc heater vary from approximately 18 to 4 volts. Since the case requirements are always less than the requirements of the disc, a single output line equal to the disc heater voltage could be used. Again there will be power unnecessarily dissipated in the controller but cost-wise this may be more feasible than having a separate line for each controller.

The cooling/heating system controller requires a negative as well as a positive voltage since the current through the thermoelectric device must be reversed when going from the cooling to the heating cycle or conversely. Hence, two lines of identical voltage values but of opposite polarity must be supplied to the controller. The value of this voltage is dependent on the repetition rate of the duty cycle controller and if this rate can be varied, the magnitude of the voltage can thus be adjusted for different values of α/ε thus increasing the efficiency in the same way as described for the heating system.

DC-AC Inverter

In order to supply the comparator with an AC driving function, it is necessary to incorporate a DC-AC inverter to make such an inversion. This AC signal must be stable since any variation in the input signal of the bridge will change the closed loop gain. In addition, the inverter should have a provision whereby the level of the output can be easily changed for each value of α/ε. These voltages are in the range of 5 volts or less. Since two comparators are required in both the heating and the cooling/heating systems, two signal lines are necessary from the inverter.

Since a phase sensitive servo amplifier is used to sense the phase relationship between the output of the bridge and the driving function, the DC-AC inverter must supply the amplifier with a reference signal of exactly the same frequency and with good amplitude stability. In order to eliminate any effects of loading, it is suggested that this reference be supplied independently of the bridge input signal.

The frequency of the required AC signal is not critical, but it should be selected within the range from 1, 000 cps to 5, 000 cps in order to keep the amplifier as simple as possible. When choosing the frequency, it should be kept in mind that the error signal will eventually be rectified and filtered. The higher the frequency, the easier it becomes to obtain lower ripple factors for given values of filter capacitors.

Comparator

The purpose of the comparator in both systems is to sense the temperature of the disc, compare the sensed temperature to a reference temperature, and express the difference between the two as an electrical signal which can be used to control the power added (heating and cooling/heating systems) or the power removed (cooling/heating system) from the disc, case or thermoelectric device. In both the heating and the cooling/heating systems the comparators are identical, being of the Siemens bridge type with a platinum resistance thermometer used as the temperature sensor. When the resistance of each arm of the bridge is equal to the maximum resistance of the thermometer, the bridge has its maximum sensitivity with the minimum self heating effect. In order to change the operating temperature, different resistance values must be used in the arms of the bridge. This change can be accomplished fairly easily if a printed circuit board is used to construct the bridge.

The output voltage of the bridge is directly proportional to the input voltage; any change in the driving voltage will be reflected into the output, hence the driving voltage must be stable.

Factors influencing the performance of the comparator are 1) temperature coefficients of the fixed resistors, 2) lead resistance, and 3) thermal conductance of the sensor leads. To minimize these problems, the fixed resistors should have as close to a zero temperature coefficient as possible, which will tend to reduce the effect of the thermal conductance of the sensor leads. Lead and contact resistance are eliminated by the three-lead compensation feature of the Siemens bridge.

AC Amplifier

Amplification of the bridge output is necessary in order to provide the controller with a sufficient driving voltage. This amplifier will see inputs on the order of 1 to 5 millivolts and should provide a variable gain control which can adjust the gain from approximately 5 to 10. The value of the gain constant will be dependent on the particular α/ϵ coating and must be set for each particular value. The frequency response requirements of the amplifier are not stringent since the inverter output and consequently the bridge output is of a constant frequency. Some selectivity, which will tend to reject undesired signals, can be accomplished by simply choosing the appropriate values of coupling capacitors and load resistors.

Smoothing Filter

The smoothing filter is shown as an individual component merely to indicate that some filtering will be necessary, but it may not exist as such since some degree of smoothing is usually associated with the servo amplifier. In both systems, the function of the smoothing filter is to filter the AC component from the DC output of the servo amplifier to such a quality that the operation of the controller will not adversely be affected. The specification of allowable ripple and consequently the detail requirements of the filter can best be made during evaluation of a prototype system.

Servo Amplifier (AC-DC Phase Sensitive

An AC-DC phase sensitive servo amplifier is merely a phase sensitive demodulator, the purpose of which is to convert an incoming AC signal to either a positive DC level or a negative DC level, depending on the phase relationship between the incoming AC signal and the reference. In the case of the cooling/heating, the bridge output is either in phase with or out of phase with the bridge driving signal depending on whether the temperature of the controlled element is either below or above the reference temperature. Hence, the two output lines turn on the appropriate output section of the controller and in effect, either adds or removes heat as required. The phase reversal of the bridge output in the heating system again means that the temperature of the controlled element is greater than the reference temperature but since the system can only add heat to the element, the output of the controller should be forced to zero for these values. This can be accomplished by inserting a blocking diode between the output of the servo amplifier and the input to the smoothing filter. When the phase detector senses a phase reversal, indicating a temperature greater than the operating temperature, the sign of the DC output is reversed. The blocking diode will restrict any flow of current and thereby present no input to the smoothing filter.

Magnetic Amplifier

A magnetic amplifier is essentially a variable-impedance device which is inserted between a source of AC power and the load in a circuit such as that shown in Figure 15. By virtue of the controllable impedance offered by the magnetic amplifier, the output current and, therefore, the load voltage and power can be controlled. The impedance of the amplifier may be varied by an independent control source. The control source for the systems being considered is a DC voltage which is proportional to the error signal in amplitude and phase.

The load and control currents are related as shown in Figure 16. It is noted that even when no control current is supplied, some residual load current exists, but this residual current is used in the heating system to prevent "lock out". In general, the magnetic amplifier requires only a control voltage and the supply voltage as inputs. The gain of a magnetic amplifier can be controlled by placing a potentiometer in the control winding. This feature should be provided to allow the necessary adjustments for the various α to ϵ ratios. It has been stated previously that the frequency of the AC supply source is relatively arbitrary. This is not the case where the magnetic amplifier is used. The response time of the magnetic amplifier improves as the supply voltage frequency increases within limits. Proper consideration should be given to the selection of the frequency for the AC supply if a magnetic amplifier is used. Because of the long period of the driving function, T_e, some common frequency satisfactory to all systems will most likely exist.

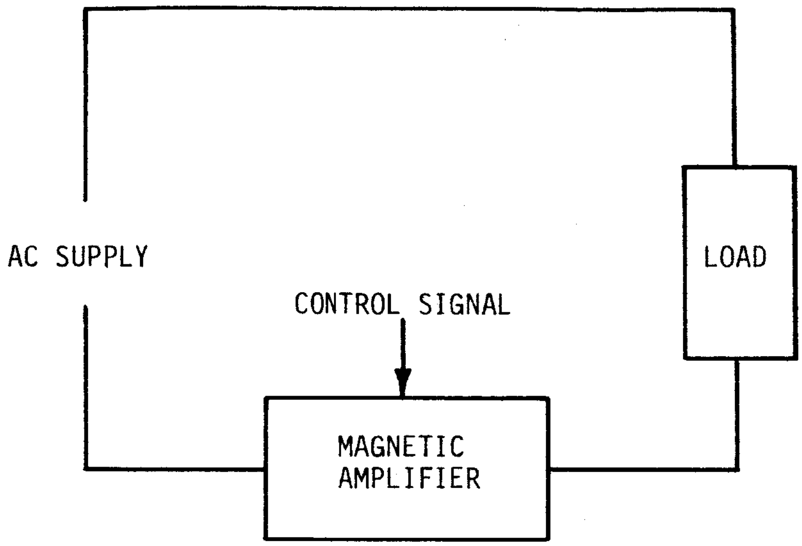

Figure 15. Magnetic Amplifier Inserted Between Source and Load

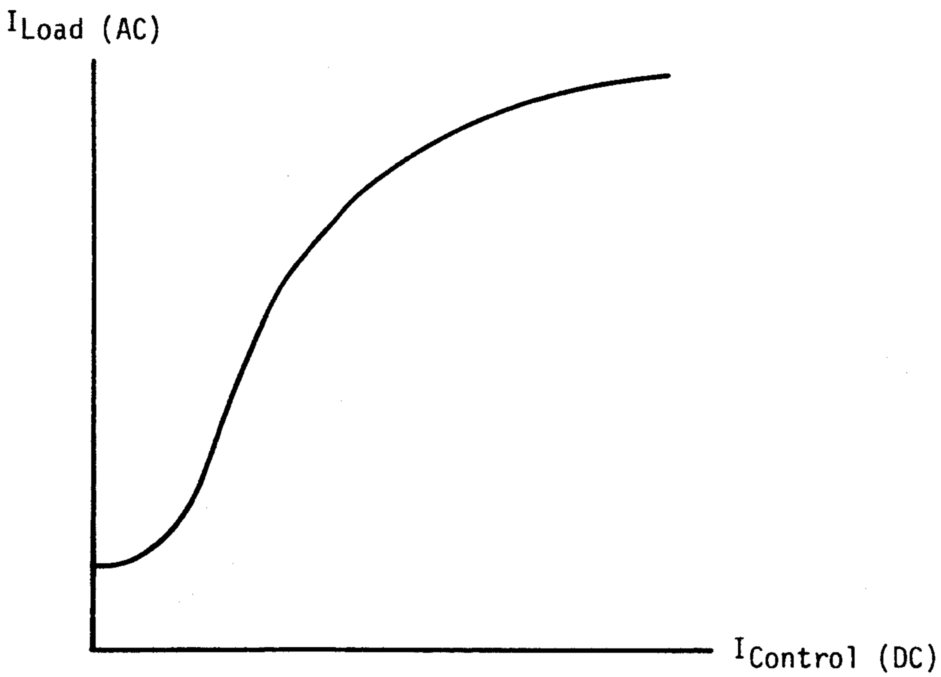

Figure 16. Load Current Versus Control Signal for a Magnetic Amplifier

Controllers

A proportional control which delivers an output current directly proportional to the input voltage is utilized by the heating system. This controller receives the heater power from the DC-DC converter and gates the power according to the magnitude of the error signal. In order that the various values of α to ε ratios may be covered by the same controller, a potentiometer should be provided in the base circuits of the input transistor so that the gain may be varied.

Heating and cooling power for the thermoelectric system is supplied by a bi-polar duty cycle controller with both positive and negative outputs available. This feature allows power to be fed through the unit in either direction thus causing heating or cooling of the disc, as indicated by the servo amplifier and selected by the gate. The repetition rate of the controller is not critical and its choice should be fairly arbitrary. The amplitude of the pulsed output should be adjustable in order that a more efficient operation may be obtained over the span of α to ε ratios.

A GUIDE FOR THE STABILITY AND ERROR ANALYSIS OF THE ASEES SYSTEMS

DYNAMIC TEMPERATURE EQUATION

The dynamic equation governing the temperature of the disc when the only energy exchange is between the actuator and the disc and that due to thermal radiation is

$$\frac{d\,T_s}{dt} = \frac{\sigma \times 10^8 \,\beta\, \varepsilon}{H}\left[\left(\frac{T_e}{100}\right)^4 - \left(\frac{T_s}{100}\right)^4\right] + \frac{P_{in}}{H} \tag{18}$$

where

T_s - the temperature of the disc (°K),

t - time (sec),

σ - Stephan Boltzmann constant $[w/m^2\,(°K)^4]$,

β - area of the disc exposed to space (m^2),

ε - emissivity of the exposed surface,

H - mass × specific heat (Joule/°K),

T_e - equilibrium temperature of the disc (°K), and

P_{in} - power supplied by the actuator (watts).

COMPONENT TRANSFER FUNCTIONS

For the heating system described by Figure 6, the power supplied by the actuator can be calculated by combining the transfer functions of the system. The various simplified transfer function of the system are given by the expressions.

Comparator

$$\frac{E_{o_1}}{E_{in_1}} = \frac{1}{2}\,\frac{R_R - (B + D\,T_s)}{R_R + (B + D\,T_s)} \tag{19}$$

where

E_{o_1} - output of the bridge (volts),

E_{in_1} - input to the bridge (volts),

R_R - reference resistance (ohms),

B - constant dependent on resistance thermometer (ohms),

D - constant dependent on resistance thermometer (ohms/°K), and

T_s - temperature of disc (°K).

AC Amplifier

$$\frac{E_{o_2}}{E_{in_2}} = k_1 \tag{20}$$

where

E_{o_2} - output of the amplifier (volts),

E_{in_2} - input of the amplifier (volts), and

k_1 - gain of the amplifier.

This transfer function is greatly simplified since the poles and zeroes of the amplifier are neglected. This simplification is justified due to the extremely long period of the driving function.

Servo Amplifier

$$\frac{E_{o_3}}{E_{in_3}} = k_2 \tag{21}$$

where

E_{o_3} - output of the amplifier (volts),

E_{in_3} - input of the amplifier (volts), and

k_2 - gain of the amplifier.

Again, the transfer function is a simplification being justified in the same manner as that for the AC amplifier.

Current Controller

$$\frac{I_{O_4}}{E_{O_4}} = k_3 \qquad (22)$$

where

I_{O_4} - output current (ampere),

E_{O_4} - input voltage (volts), and

k_3 - gain of current controller (ampere/volts).

The same statement concerning simplification applies as in the two preceding cases.

Heater

$$P_{out} = I_{O_4}^{\,2} R_H \qquad (23)$$

where

I_{O_4} - output current of the controller (ampere),

R_H - resistance of the heater (ohms), and

P_{out} - output power of heater (watts).

Expressing the output power of the heater in terms of the temperature of the disc and the parameters of the system, Equation 23 can be written as

$$P_{out} = \frac{k_1^2 k_2^2 k_3^2 E_{in_1}^{\,2} R_H}{4} \left[\frac{R_R - (B + D\,T_s)}{R_R + (B + D\,T_s)}\right]^2 \qquad (24)$$

and

$$R_R = A\,T_R$$

where

R_R - reference resistance (ohms), and

A, B, and D - constants determined by the properties of the resistance thermometer.

Therefore,

$$P_{out} = \frac{k_1^2 k_2^2 k_3^2 E_{in_1}^2 R_H}{4} \left[\frac{A\, T_R - (B + D\, T_s)}{A\, T_R + (B + D\, T_s)} \right]^2 \tag{25}$$

or

$$P_{out} = \frac{k_1^2 k_2^2 k_3^2 E_{in_1}^2 RH}{4} \left(\frac{A^2 T_R^2 - 2 A B T_R - 2 A D T_R T_s + B^2 + 2 B D T_s + D^2 T_s^2}{A^2 T_R^2 + 2 A B T_R + 2 A D T_R T_s + B^2 + 2 B D T_s + D^2 T_s^2} \right) . \tag{26}$$

Substitution of Equation 26 into Equation 18 yields

$$\frac{d\, T_s}{dt} = 4.2883 \times 10^{-3}\, \varepsilon\, T_e^4 - 4.2883 \times 10^{-3}\, \varepsilon\, T_s^4$$

$$+ \frac{k_1^2 k_2^2 k_3^2 E_{in_1}^2 RH}{4} \left(\frac{A^2 T_R^2 - 2 A B T_R - 2 A D T_R T_s + B^2 + 2 B D T_s + D^2 T_s^2}{A^2 T_R^2 - 2 A B T_R + 2 A D T_R T_s + B^2 + 2 B D T_s + D^2 T_s^2} \right) . \tag{27}$$

Equation 27 describes the system and can be represented by the block diagram of Figure 17. This equation represents a closed loop, nonlinear control system which can possibly be unstable or conditionally stable.

The ability of any control system to follow its input is dependent on the magnitude of the disturbances and their frequency of occurrence. These two factors alone impose certain requirements on the gain and frequency response of the system. For rapidly changing disturbances, the system must be able to change as fast as these disturbances and also have sufficient gain to overcome the magnitude of the disturbances. In any stable control system, the steady state error, ε, is related to the output, θ_C, by the expression

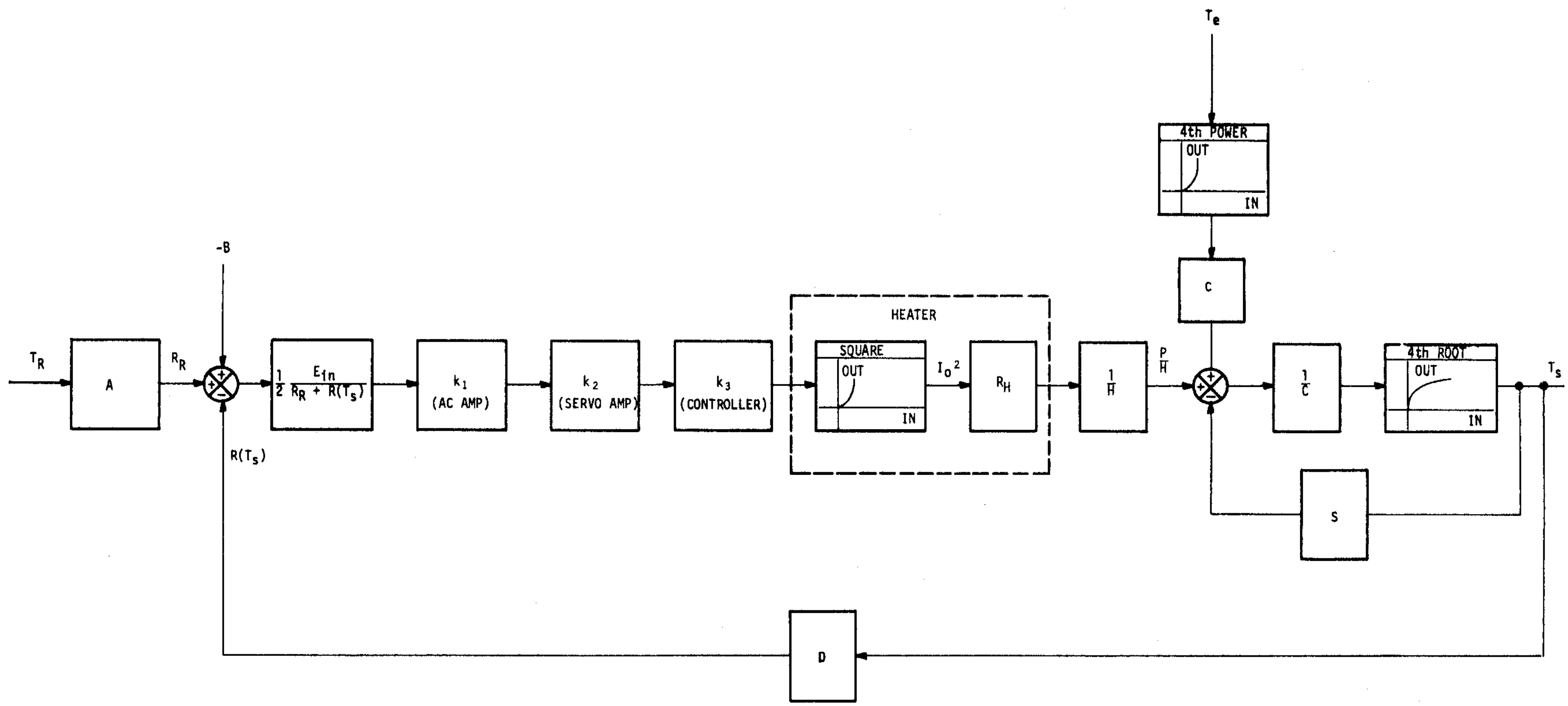

Figure 17. Mathematical Block Diagram Representing the Heating System

$\theta_c(s) = \varepsilon\, s^n k E(s)$ where k is the gain of the system, n is the order of the system and s is the Laplace transform variable. Hence, the expression clearly indicates that an increase in gain reduces the error. However, an increase in gain while tending to reduce the error also tends to destabilize the system. Thus, some compromise between error and relative stability must be reached.

To determine stability of the systems and the possible conditions for stability, many solutions must be obtained for various values of the product k_1, k_2, k_3, and initial conditions. Due to the high degree of nonlinearity, conventional techniques used in the analysis of control systems are not applicable and an analysis based on the transient response of the system seems to be the most straightforward.

In order to perform an error analysis, suitable values of gains must be established. Once this is done and the performance of the system is satisfactory with these values, the right side of Equation 27 can be set to zero and the remaining sixth degree algebraic equation in T_s can be solved. Since this equation is based on a physical system, the proper roots can be recognized. This expression for T_s can then be used to find the variation of T_s with changes in a particular system parameter by taking the first partial derivative with respect to that parameter and setting that expression equal to zero. In this method all other parameters are held at their nominal values.

The same procedure can also be applied to the thermoelectric system. The block diagram for this system is shown in Figure 18. As is shown by Figure 18, the thermoelectric system is considerably more complex due to the nonlinear equation of the thermoelectric device itself. This equation is given by

$$Q = \alpha\, T_s I - \frac{1}{2} I^2 R - K\,(T_{HS} - T_s) \qquad (28)$$

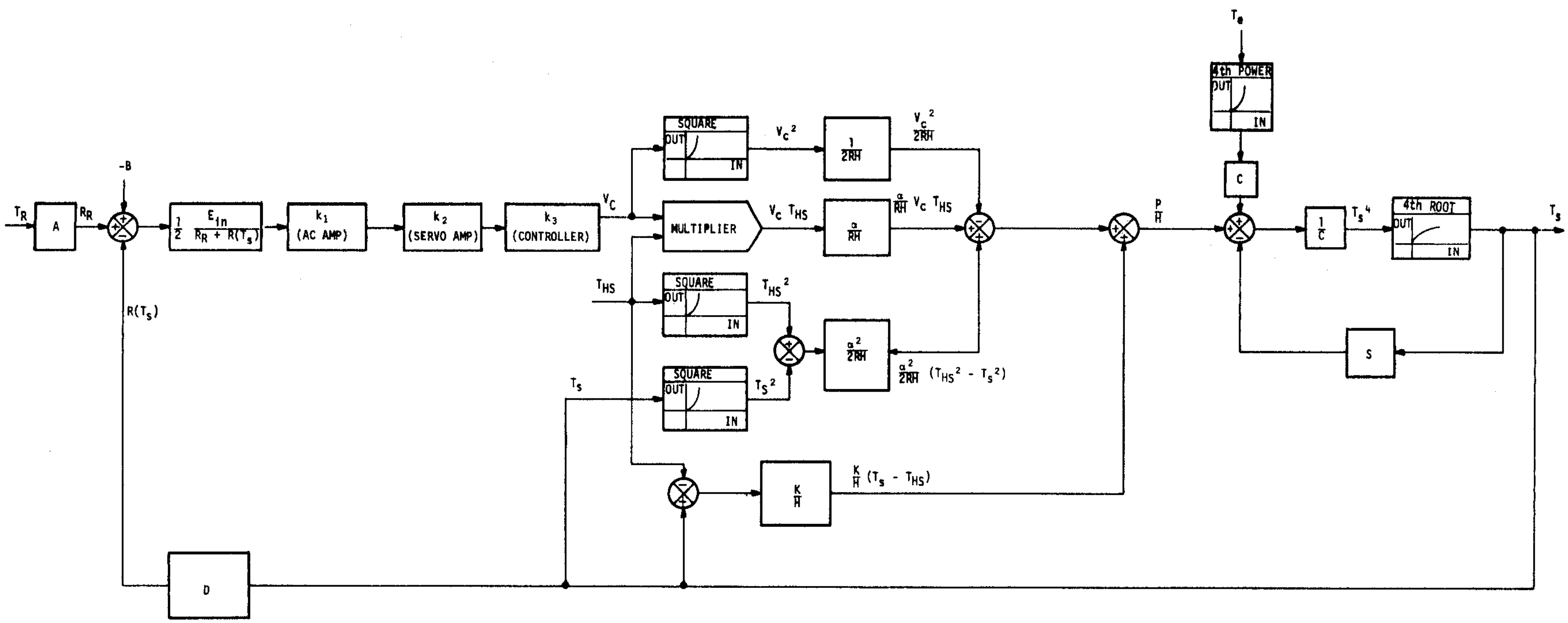

Figure 18. Mathematical Block Diagram Representing the Cooling/Heating System

where

Q - the rate of cooling (watts),

α - summation of the magnitude of the Seebeck coefficients of the two arms of the device (volts/°K),

T_s - temperature of the disc (°K),

T_{HS} - temperature of the upper heat sink (°K),

R - electrical resistance of the two arms of the device (ohms),

K - thermal conductance of the two arms of the device (watts/°K), and

I - current (amperes).

The power input to the device is given by

$$P = \alpha (T_{HS} - T_s) I + I^2 R \quad . \tag{29}$$

If V_c is the output voltage of the controller, the rate of cooling can be expressed as

$$Q = \frac{\alpha^2}{2R} T_s^2 + K T_s - \frac{V_c^2}{2R} + \frac{\alpha V_c T_{HS}}{R} - \frac{\alpha^2 T_{HS}^2}{2R} - \frac{K T_{HS}}{H} \quad . \tag{30}$$

By expressing V_c in terms of the system parameters and substituting Q/H for P_{in}/H in Equation 18, an expression for the thermoelectric system similar to that for the heating system can be constructed. The procedure for an error analysis is then the same as that described for the heating system.

CONCLUSIONS AND RECOMMENDATIONS

It is concluded from this study that an ASEES using active heating or cooling and heating is feasible. The estimated static error for disc temperature is 1.0 degree for the active heating system. An estimate of the static error for the cooling/heating system and dynamic error for both systems cannot be made until additional stability studies are made. Additional development and testing are recommended in order to substantiate the results of the feasibility study.

The important results and estimated characteristics of both the active heating system and the cooling/heating system are summarized in Table 1.

The power requirements for the different systems are strongly dependent upon the α/ε ratios. As a result, comparisons must be made for each value of α/ε. Shown in Table 2 are the total energy requirements, in Watt-minutes, for one complete orbit. Two cases are included for the cooling/heating system. In the optimum case both the controlled and uncontrolled heat sinks of the thermoelectric module are at the same temperature. In the worst case, the uncontrolled heat sink is 40°K below the temperature of the controlled heat sink. Details of the power requirements are presented in Reference 3.

The estimated accuracy of the active heating system is based on a preliminary stability study of the system which indicated a maximum error of 7°K. This error was obtained when the theoretical values for system parameters were used to evaluate the time response of the system. It is felt that further gain adjustments would reduce the error to 1°K. Additional analyses were not attempted due to the large amount of computer time required to evaluate the time response of the system. Since the expression for the cooling/heating system is considerably more complex than that for the heating system, no calculations of response were made for the system, hence no figures are available for an estimate of that system's accuracy.

TABLE 1

ESTIMATED CHARACTERISTICS OF PROPOSED ASEES

Characteristic	Active Heating Separate	Active Heating Combined	Cooling/Heating
Accuracy	1 °K	1 °K	---
Weight	80 oz	90 oz	90 oz
Life Expectancy	Limited only by satellite power supply		
Component Development	None	None	Thermoelectric Device
Energy Requirement	-------------See Table 2-------------		

TABLE 2

ESTIMATED ENERGY* REQUIREMENTS
FOR ONE COMPLETE ORBIT

α/ε	Heating Only	Cooling/Heating Optimum	Cooling/Heating Worst Case
0.2	23.8	28.3	257
0.4	41.7	13.0	242
0.8	76.8	18.9	218
1.0	92.9	24.9.	208
2.0	89.5	24.2	200
4.0	89.8	24.7	194
10.0	89.3	22.8	193

*Energy values in Watt-minutes.

All components used by the active heating system are of conventional design and are either immediately available or can be constructed by only slightly modifying components presently available. All components for the cooling/heating system fall in the same category with the exception of the thermoelectric device. This component will require extensive development.

Outlines of suggested future work on the ASEES systems are shown in Figure 19. The outline for the cooling/heating system is identical to that for the active heating system except that the former requires some component development while the latter does not.

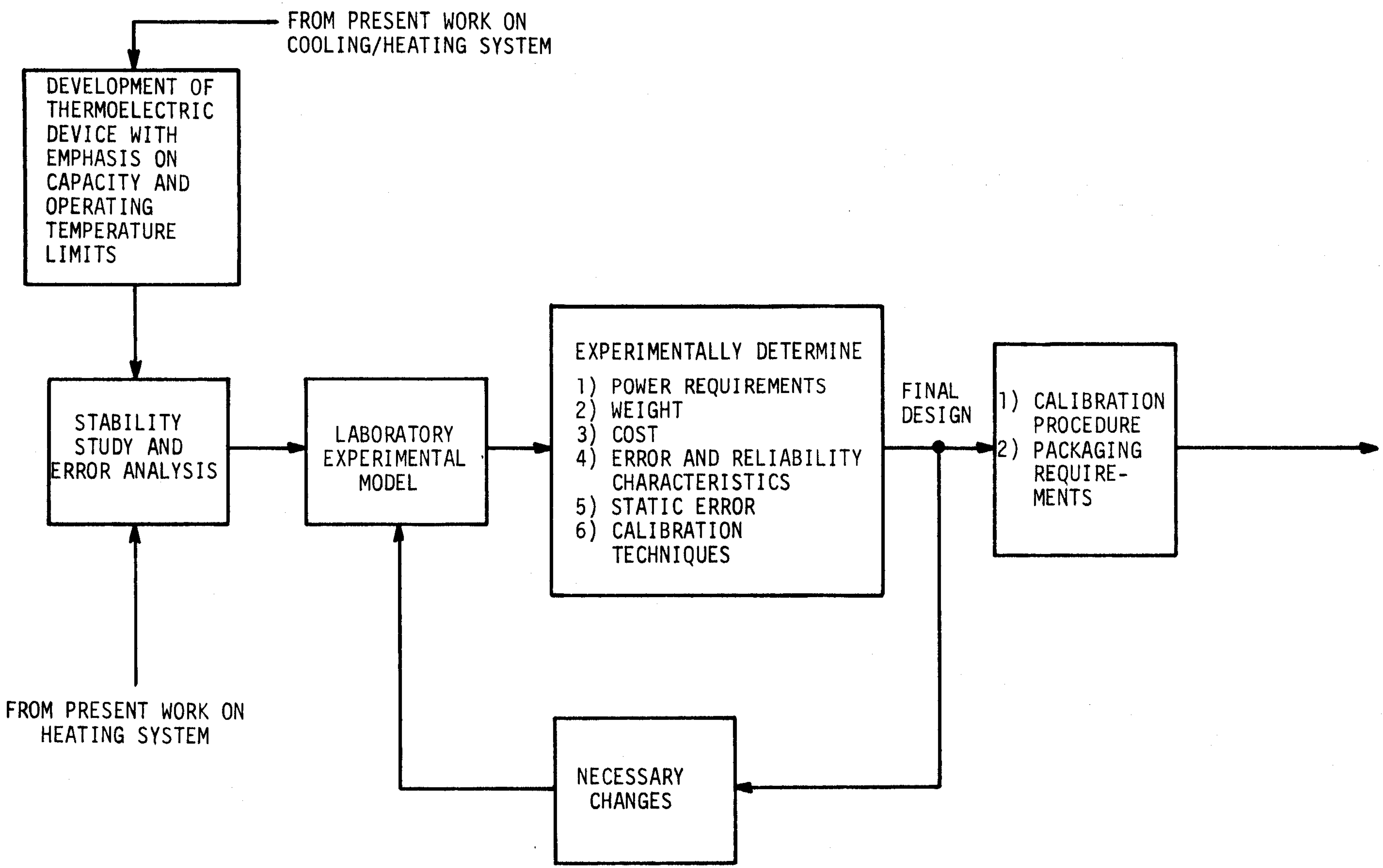

Figure 19. Flow Diagram of Suggested Future Work on Heating System

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13. ABSTRACT

This report summarizes the results of a feasibility study of an Advanced Space Environmental Effects Sensor (ASEES) using active control of sensor temperature. A detailed thermal analysis is presented followed by conceptual designs of three possible systems, two using active heating and a third using a thermoelectric module for active cooling/heating. Guidelines for a stability and error analysis are included as well as recommendations for further studies.

14. KEY WORDS

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active control